

Two Confirmed Cataclysmic Variables in the Old Stellar Cluster NGC 6791¹

J. Kaluzny

Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland

e-mail: jka@sirius.astro.uw.edu.pl

K. Z. Stanek², P. M. Garnavich, P. Challis

e-mail: kstanek@cfa.harvard.edu, pgarnavich@cfa.harvard.edu,

challis@cfa.harvard.edu

Harvard-Smithsonian Center for Astrophysics, 60 Garden St., MS20, Cambridge, MA 02138

ABSTRACT

Based on new CCD photometry and spectroscopy we confirm the presence of two cataclysmic variables (CVs) in the very old open cluster NGC 6791. One of these variables, known as B8, was observed by Rucinski, Kaluzny & Hilditch (1996) to undergo a large magnitude outburst in 1995. The spectrum of this star outside the outburst, obtained by us with MMT, shows clearly the emission lines characteristic for dwarf novae. We observed the second star, known as B7, to undergo large (~ 3 mag) drop in its brightness over ~ 10 days. The spectrum of B7 obtained in the high state resembles spectra of nova-like CVs. This star is a likely member of UX UMa subtype of CVs. Variables B7 and B8 represent only the second and the third cataclysmic variables known in open clusters. Variable B7 has observational characteristics which would make it difficult to identify as a CV with some of the methods being currently used in surveys for CVs in globular clusters.

Subject headings: open clusters and associations – individual: NGC 6791 – stars: variables

¹Based on the observations collected at the Michigan-Dartmouth-MIT (MDM) 1.3-meter telescope, the F. L. Whipple Observatory (FLWO) 1.2-meter telescope and the Multiple Mirror Telescope (MMT).

²On leave from N. Copernicus Astronomical Center, Bartycka 18, Warszawa 00-716, Poland

1. INTRODUCTION

NGC 6791 is currently considered to be the one of oldest known open clusters in the Galaxy. Recent photometric work includes studies by Kaluzny & Udalski (1992, hereafter: KU), Montgomery, Janes & Phelps (1994), Garnavich et al. (1994) and Kaluzny & Rucinski (1995, hereafter: KR95). There is a spectroscopic as well as a photometric evidence that the cluster metallicity is a factor of 2–3 higher than the solar value (Friel & Janes 1993; Garnavich et al. 1994; KR95). NGC 6791 is also one of the most massive open clusters currently known with the total mass of observed stars exceeding $4000M_{\odot}$ (KU).

NGC 6791 is unique among old open clusters in harboring a group of hot subdwarfs. KU identified 8 faint blue stars in the cluster field based on *BVI* photometry. They suggested that these objects are hot subdwarfs belonging to the cluster. Two additional candidates for hot subdwarfs were identified by KR95 who provided also $U - B$ colors for all candidates. Some of these blue stars were observed by Liebert et al. 1994 and indeed found to be hot subdwarfs and likely members of the cluster (see also Green et al. 1996).

Most of the previous studies concentrated on the age and metallicity of the cluster and only two searches for variable stars in NGC 6791 have so far been conducted (Kaluzny & Rucinski 1993, hereafter: KR93; Rucinski, Kaluzny & Hilditch 1996, hereafter: RKH), leading to discovery of 8 contact binaries and 14 other variables, with many among the latter being detached eclipsing systems. A fraction of these variables are likely to be foreground field stars.

The main motivation of the present study was to provide a continuation to variability studies of KR93 and RKH. Our intention was to monitor long-term variability of stars in NGC 6791. The detailed results of the CCD photometry obtained for the 10.9×10.9 *arcmin* region of the cluster will be presented elsewhere (Stanek & Kaluzny 1997, in preparation). In this Letter we confirm the presence of *two* cataclysmic variables in NGC 6791, which presence was suspected based on earlier data (KR93; RKH; Liebert et al. 1994). Although several cataclysmic variables are either detected or suspected in globular clusters (Grindlay et al. 1995; Livio 1996; Bailyn et al. 1996), we note that these two stars are the second and third cataclysmic variables known in old open clusters. The first such system was detected by Gilliland et al. (1991) in M 67.

2. NEW OBSERVATIONS

We obtained photometric data on 30 nights between September 8 and November 1, 1996. NGC 6791 was primarily observed with the McGraw-Hill 1.3-meter telescope

at the MDM Observatory. We used the front-illuminated, Loral 2048² CCD Wilbur (Metzger, Tonry & Luppino 1993), which at the $f/7.5$ station of the 1.3-meter has a pixel scale of $0.32 \text{ arcsec/pixel}$ and field of view of roughly 10.9 arcmin . We used Kitt Peak Johnson-Cousins BVI filters. Some data for NGC 6791 were also obtained with the 1.2-meter telescope at the FLWO, where we used “AndyCam” with thinned, back-side illuminated, AR coated Loral 2048² CCD (Caldwell et al. 1996). The pixel scale happens to be essentially the same as at the MDM 1.3-meter telescope. We used standard Johnson-Cousins BVI filters (Caldwell et al. 1996). We obtained for NGC 6791 useful data during 25 nights at the MDM, collecting a total of 79 450 *sec* exposures in V and 50 300 *sec* exposures in I . We obtained additional data during 5 nights at the FLWO, collecting a total of 30 450 *sec* exposures in V and 4 300 *sec* exposures in I .

The profile photometry was extracted using Daophot/Allstar programs (Stetson 1987). More detailed description of applied procedures is given in Kaluzny et al. (1997). Transformations to the standard VI_C system were obtained by calibrating out the color terms using Landolt (1992) fields and determining the zero-point offsets with the KU data.

Spectra of B7 and B8 were obtained with the Multi-Mirror Telescope (MMT) and Blue Channel Spectrograph. Exposures of B7 were taken on April 8, May 2 and 3, 1997, while data for B8 were obtained on April 7, 1997. A 300 line/mm grating was used with a 1 arcsec slit at the parallactic angle providing a resolution of 7\AA FWHM and spectral coverage from 3200\AA to 8000\AA . The seeing was better than 1.0 arcsec on all the nights, so the slit losses were small.

3. RESULTS FOR THE VARIABLES

3.1. The cataclysmic variable B8

Several blue stars were discovered by KU and KR95 in NGC 6791, among them B8. As was pointed out by KR95, the very blue color of B8 and its variability strongly suggested a cataclysmic variable. The photometry of RKH supported this supposition. The star showed a distinct outburst characteristic for dwarf novae stars which lasted a few days and had an amplitude of about 2 mag in V (Fig.1, left panel). The star became distinctly bluer during this outburst (see the CMD of the cluster in Fig.5), which is typical for a stronger contribution of the accretion disk to the combined color. The data before the outburst of B8 show relatively large scatter, much exceeding the random errors of RKH photometry. They attempted a formal analysis for presence of periodicities and saw a weak signal at 30.36 cycles per day (47.4 minutes), with a small amplitude of 0.20 mag, only slightly larger than

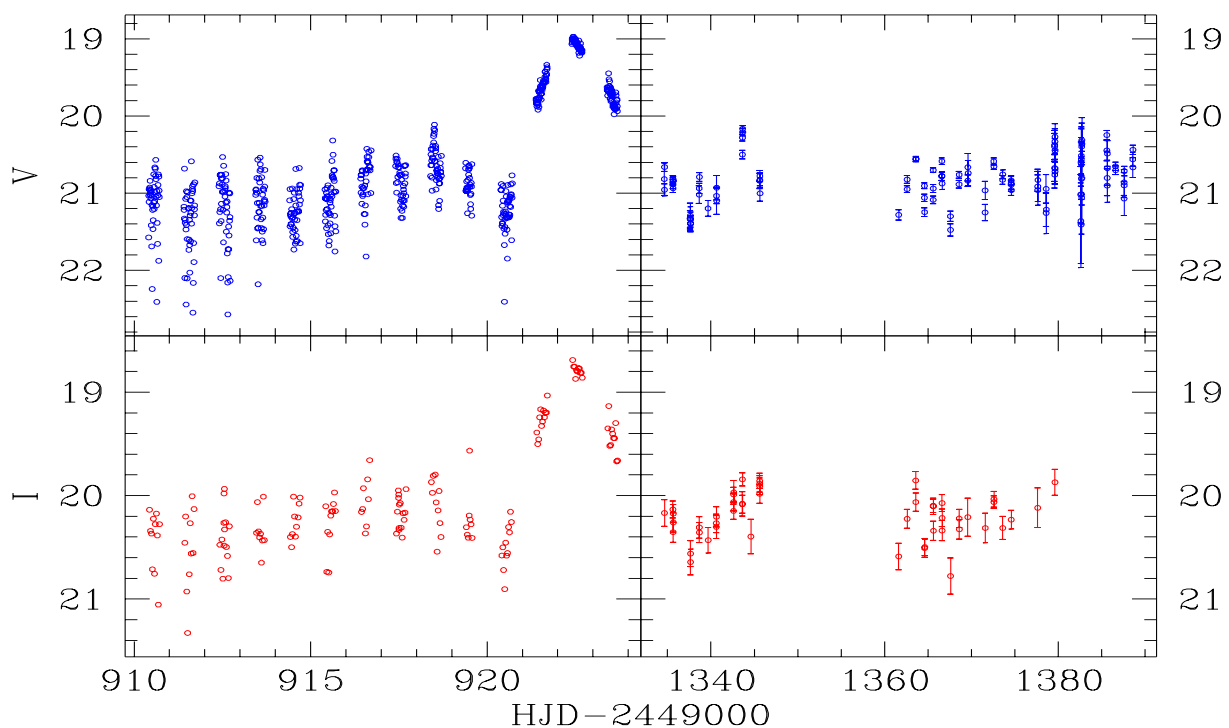


Fig. 1.— V (upper panels) and I (lower panels) light curves of the cataclysmic variable B8. Note that the ranges of the horizontal axis are different for the 1995 data (left panels) and the 1996 data (right panels.)

the random errors of their photometry. This suspected periodicity requires confirmation with more accurate data.

Additional VI photometry for B8 was obtained by us during September-October 1996 (Fig.1, right panel). The star showed overall changes of luminosity between $V \sim 20.2$ and $V \sim 21.2$. On some nights we observed variability reaching $0.5\ mag$ on a time scale shorter than $1\ hour$.

The spectrum of B8 (Fig.2) shows Balmer emission lines on a blue continuum. A strong HeI line at 4471\AA is also seen, but no HeII 4686 is detected. The bright Balmer lines are resolved and show widths of about $2000\ km\ s^{-1}$ FWHM. The equivalent width of $H\beta$ is $30 \pm 5\text{\AA}$. The V magnitude estimated from the flux between 5000 and 6000\AA is 21.0 , consistent with the variable being in its low state. Overall, the spectrum is that of a cataclysmic variable in quiescence.

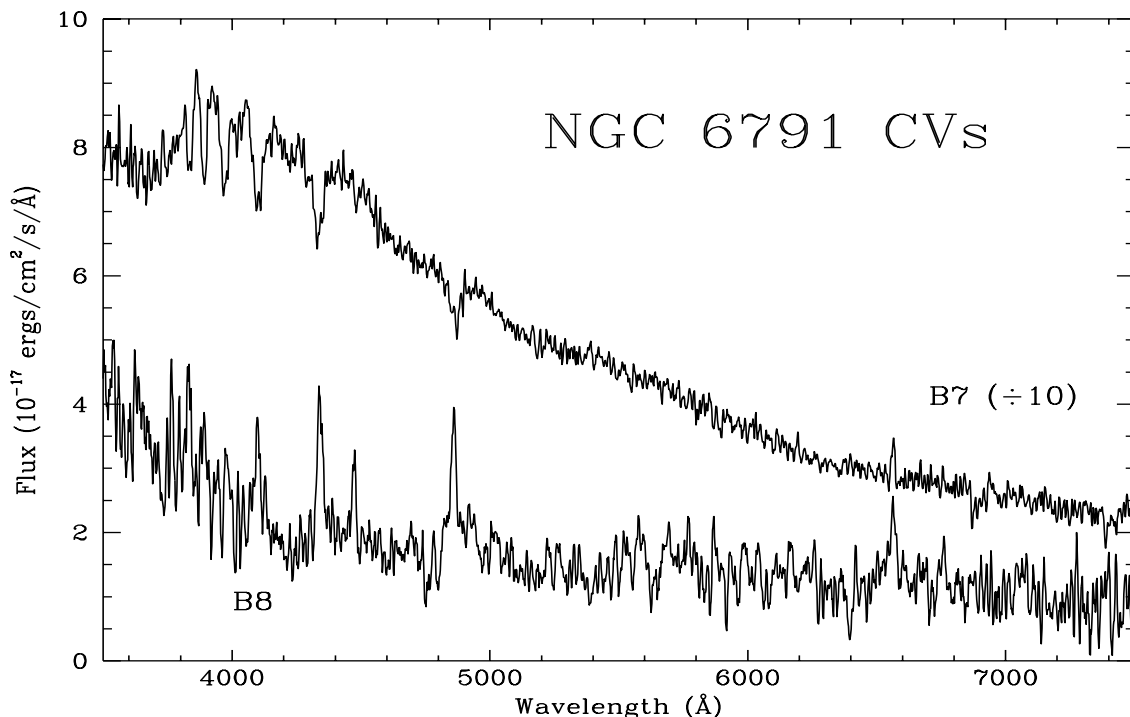


Fig. 2.— MMT spectra of the variables B7 and B8 in NGC 6791. Please note that the flux of B7 was scaled down by a factor of 10.

3.2. The cataclysmic variable B7

B7 was also discovered by KU as one of the stars with very blue color. KR93 found B7 to be weakly variable. The star changed its V magnitude from 17.68 to 17.84 over 4 consecutive nights in October, 1991. In the left panel of Fig.3 we show the light curve of B7 based on the data published by KU, KR93 and KR95. The stars was observed on a total of 11 nights between June 1990 and October 1992. B7 was not observed by RKH as it fell outside their field of view. Liebert et al. (1994) obtained spectroscopy for B7 and found it to have very broad, shallow hydrogen and helium absorption lines, with narrow emission cores, resembling a cataclysmic variable with an optically thick accretion disk.

Our additional photometry obtained for B7 during September-October 1996 is presented in the right panel of Fig.3. The star underwent a dramatic $> 3\ mag$ drop in its brightness over the course of ~ 10 days and then went back to its “high” level over the next 10 – 15 days, although we did not observe it on the rise. It then continued to vary slowly throughout October 1996, but with smaller variations of up to $0.6\ mag$.

Our spectrum of B7 taken on April 8, 1997, shows a blue continuum with $H\beta$ and higher in absorption. The $H\alpha$ line is reversed and seen as pure emission. The observed flux is consistent with the spectrum being taken at optical maximum. The spectra taken in May

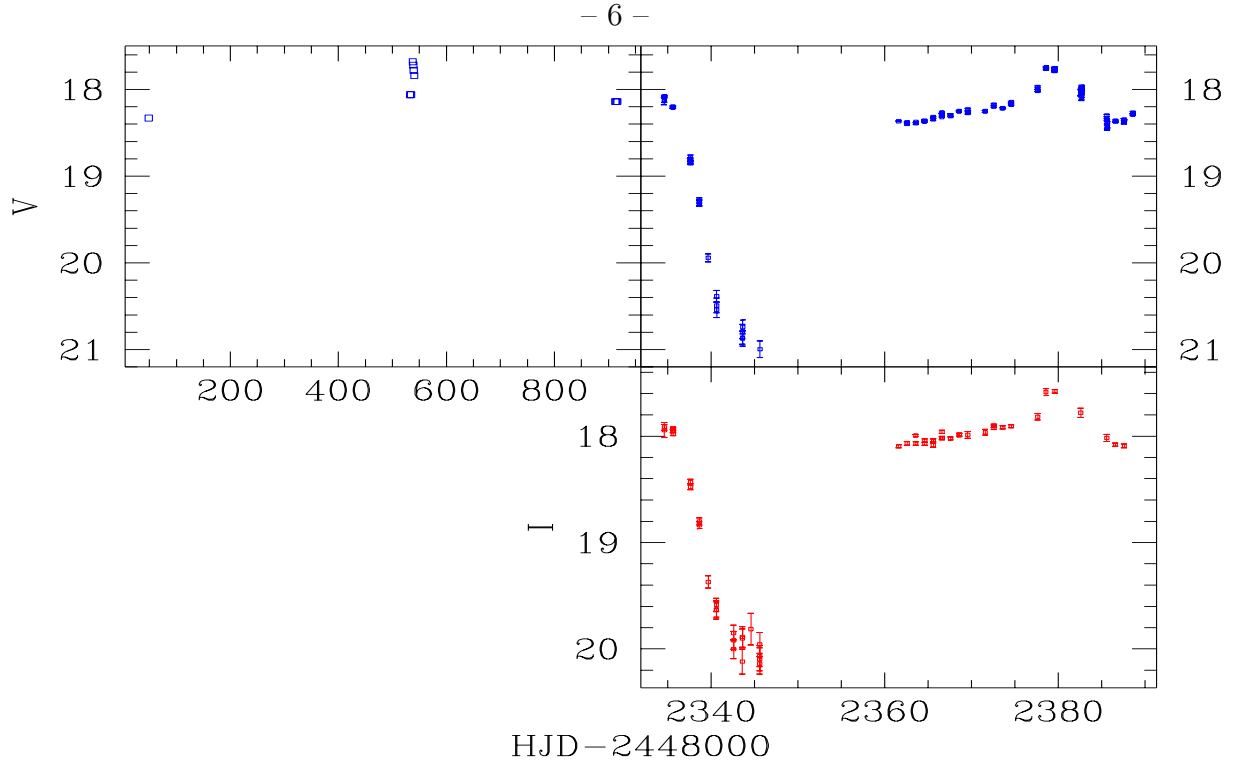


Fig. 3.— V (upper panels) and I (lower panel) light curves of the cataclysmic variable B7. Note that the ranges of the horizontal axis are different for the 1990-92 data (left panel) and the 1996 data (right panels.)

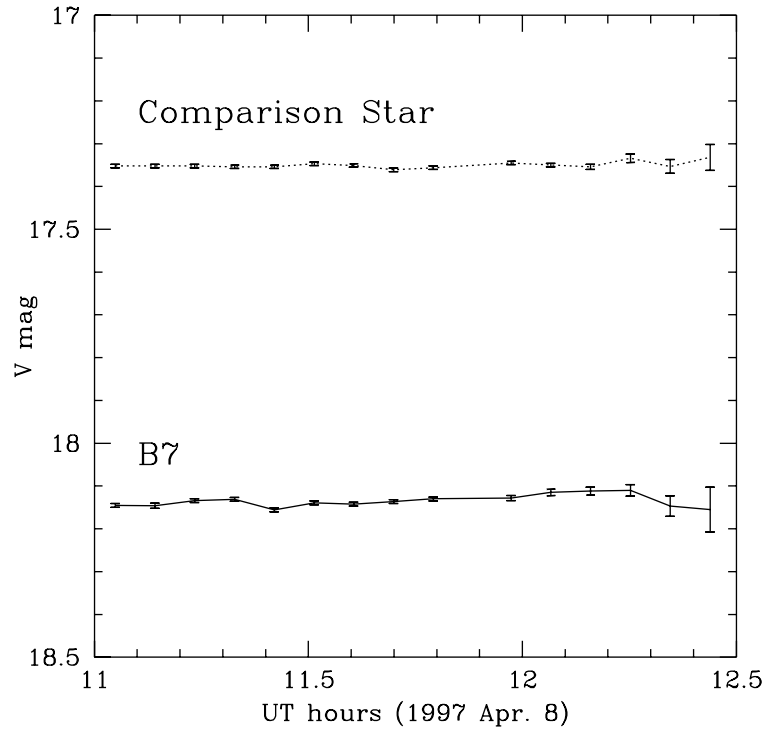


Fig. 4.— V -band light curve of B7 obtained with the 2.1-m KPNO telescope on April 8, 1997.

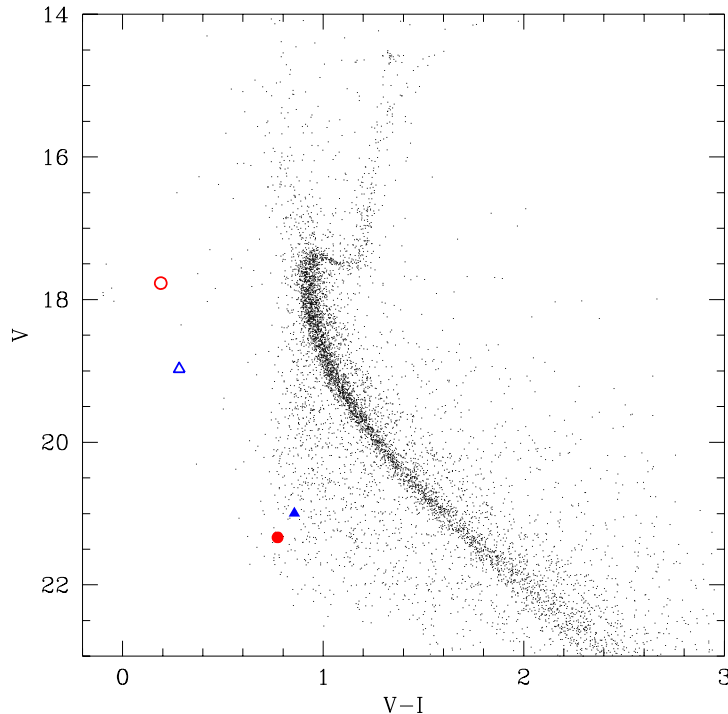


Fig. 5.— $V, V - I$ color-magnitude diagram for the NGC 6791 cluster. Filled symbols represent the low states of B7 (triangle) and B8 (circle) variables and open symbols represent the high states of these variables.

show only weak Balmer absorption and the flux implies that the CV was caught outside a high state with $V \approx 19$.

The variable B7 was also monitored for 1.5 hours on April 8, 1997, using the KPNO 2.1-meter telescope and direct CCD camera. Fifteen 300 *sec* exposures were obtained with a standard Harris V filter and the results of the differential photometry are shown in Fig.4. The dawn increase in sky brightness terminated the sequence, and the effect of the rising background is reflected in the larger error bars for the last few exposures. The star showed very little variability and there is no clear signature of flickering or orbital modulation, although a longer monitoring interval is needed to rule out the latter. The measured magnitude $V = 18.13$ corresponds to B7 being in the high state, in agreement with the MMT spectrum taken on the same night.

4. DISCUSSION

In Fig.5 we show a $V, V - I$ color-magnitude diagram for the NGC 6791 cluster, along with the low (filled symbols) and high (open symbols) positions of B7 (triangle) and B8

(circle) variables. The spectra of B7 and B8 (Fig.2) demonstrate that these are cataclysmic variables. The light curve of B8 suggests that it is a dwarf nova. The amplitude for the outburst observed in 1995 was 2.0 *mag* in *V*, which is a relatively small range for dwarf novae. From the Kukarkin-Parenago relationship, the outburst recurrence time for B8 should be in the range of 10 to 30 days (Warner 1987). However, so far the variable was caught only once in a clear outburst.

Photometrically B7 is seen in the high state most of the time, and four spectra have failed to catch the CV at minimum. We speculate that B7 is a nova-like CV which spend most of their time at a high mass transfer rate with occasional dips to quiescence. Such behavior is exhibited by some members of UX UMa sub-type of CVs (Warner 1995). The nova-like variables spending most of the time in a high state, but occasionally falling in brightness by one or more magnitudes are known also as VY Scl stars. However, long-term monitoring is needed to confirm this classification. Optionally, B7 can belong to Z Cam subtype of CVs which have periods of “standstill” at magnitudes intermediate between minimum and maximum. The spectra of B7 obtained at a high state resemble spectra of some well studied UX UMa type stars.

It is worth to note that B7, while in high state, would be difficult to identify as a CV using two methods most often applied to look for the CVs in the centers of globular clusters. The first method is based on searching for photometric variability. As can be seen in Fig.3, B7 was showing relatively little variability for 13 consecutive nights after recovery from the low state. A striking example of lack of easily detectable variability in the light curve of B7 is shown in Fig.4. The visual magnitude of B7 was constant to within about 0.035 during 1.5 hour of monitoring. The light curve is free of flickering, a usual signature of light curves for most of the CVs. The second method often used to look for the CVs in clusters is based on selecting objects with strong emission in Balmer lines. Such objects are selected based on a photometric index obtained from photometry through broad band and narrow band filters. One of our spectra of B7 (see Fig.2) shows only weak emission in $H\alpha$ and no emission at all in higher lines of the Balmer series. The remaining spectra show all of the Balmer lines in absorption.

The apparent distance modulus of NGC 6791 is $(m - M)_V = 13.65$ (Garnavich et al. 1994) so we can convert the observed *V*-band minimum and maximum into absolute magnitudes. Thus for B7 and B8 we find minimum absolute magnitudes of $M_V = 7.4$ and $M_V = 7.6$, respectively. The $H\beta$ equivalent width measured for B8 during quiescence predicts an absolute magnitude of ~ 8 from Patterson’s (1984) empirical fit, which is reassuringly close to our measured value.

While we cannot determine the orbital periods of these two CVs from their photometric

variability, we can use their absolute brightnesses at maxima to estimate periods based on the correlation given by Warner (1987). For B7, the absolute visual magnitude at maximum is $M_V = 4.4 \text{ mag}$, so the period is expected to be approximately 4.8 *hour* for normal outbursts. If B7 were a Z Cam star observed during a standstill, then the orbital period would be substantially longer. The absolute magnitude of the system at minimum places a constraint on the maximum period if we assume the secondary fills its Roche lobe. The secondary cannot be brighter than $M_V \sim 7.6 \text{ mag}$, so the orbital period cannot be longer than 6 *hour* if the secondary is a normal dwarf (Caillault and Patterson 1990).

B8 is apparently fainter at maximum than B7, but only one maximum has been observed and this makes the period estimate uncertain. For the single maximum we find an absolute magnitude of $M_V \sim 5.2$ corresponding to a period of 1.7 *hour*. This is below the period gap and may mean that B8 is an SU UMa star. Further monitoring is needed to search for superoutbursts.

The two CVs discussed in this paper were originally selected based on their blue colors and photometric variability.³ None of the remaining nine blue stars with $V < 19$ identified in NGC 6791 by KU and KR95 had shown so far any evidence for variability exceeding a few hundreds of magnitude. However, we note that several faint blue objects with $V < 21.5$ were detected in the cluster field by KR95. If among these stars there were some intrinsically faint CVs they would not be detected as variables neither in our survey nor in KR93 survey. In particular, we note that AM Her-type object detected in M67 by Gilliland et al. (1991) would not have been detected by us as variable star at the distance of NGC 6791.

It is remarkable that three CVs were discovered serendipitously in two old open clusters (M67 and NGC 6791), while few CVs were identified so far in dedicated surveys of centers of nearby globulars performed with the HST (Grindlay et al. 1995). The samples of stars observed in such clusters as NGC 6397 (Grindlay et al. 1995) and NGC 6752 (Bailyn et al. 1996) are of comparable size to our sample of NGC 6791 stars. It is expected on theoretical grounds that large numbers of CVs should be formed in GCs through two body tidal capture. Central densities of NGC 6791 and particularly M67 are very low in comparison with post-collapse clusters like NGC 6397 and NGC 6752. Most likely CVs observed in M67 and NGC 6791 evolved from primordial binaries and were not formed through two body tidal capture. Putting all this together, it seems that at least some

³ As may be seen in Fig.5, B7 and B8 exhibit relatively red V-I colors while in low state. B8 is, however, blue in $B - V$ and particularly in $U - B$ color even when in low state (KR95). The same holds most probably also in case of B7, although observational data to support that are lacking at present.

fraction of CVs observed in globulars also descend from primordial binaries. That makes even more serious the discrepancy between predictions of the tidal capture theory and observed low number of CVs in GCs (eg. Livio 1996).

We note parenthetically that NGC 6791 could be classified as a young, low concentration globular cluster of extremely high metallicity. Considering its richness, NGC 6791 is better populated than several sparse globular clusters, such as E3 (Hesser et al. 1985). Moreover, its luminosity function is flat for at least 5 *mag* below the turnoff (KR95), while the luminosity functions of other old open clusters show turnover 3 – 4 *mag* below the turnoff (Montgomery et al. 1993; Caputo et al. 1990). Also the age of NGC 6791 is close to ages of some “young” galactic globular clusters. In particular the principal sequences on the CMDs of NGC 6791 (KR95) and globular cluster Ter 7 (Buonanno et al. 1995) match very well, if appropriate shifts in color and magnitude are applied. The ages of these two objects must be very close to each other. Buonanno et al. (1994) noted that four exceptionally young galactic globular clusters (Ter 7, Arp 2, Ru 106 and Pal 12) are all located on a great circle on a sky. They suggest that these young GCs could be captured by the Milky Way from a companion galaxy. NGC 6791 does not lay on the great circle defined by positions of four clusters discussed by Buonanno et al. (1994). However, the cluster does show a peculiar motion for an open cluster. It orbits the galactic center on highly eccentric orbit with the galactocentric distance ranging from 4 to 10 *kpc* (Anthony-Twarog 1996). In respect to metallicity NGC 6791 resembles a few super metal-rich globulars located close to the galactic center. Taking into account high metallicity of NGC 6791 we may speculate that it was formed near the galactic center as a massive cluster and then kicked out on its present day orbit as a result of encounter with a massive molecular cloud or interaction with a passing dwarf galaxy. Such an event would lead to significant reduction of the mass of the cluster.

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